CLAIMS

1. A method for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, the workpiece having a surface hardness, comprising increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool.

2. A method as in claim 1, wherein the surface hardness of the workpiece is increased by cooling with a cryogenic fluid at least a portion of the tool, or at least a portion of the workpiece, or at least a portion of the tool and at least a portion of the workpiece.

3. A method as in claim 2, wherein a jet of the cryogenic fluid impinges on a portion of the tool and a portion of a surface of the workpiece.

4. A method as in claim 3, wherein the jet of the cryogenic fluid impinges on the portion of the tool at an impingement angle (α) greater than about 0° and less than about 90°.

5. A method as in claim 3, wherein the jet of the cryogenic fluid impinges on the portion of the tool at an impingement angle (α) greater than about 30° and less than about 90°.

6. A method as in claim 3, wherein the jet of the cryogenic fluid impinges on the surface of the workpiece at a spread angle (β) greater than about 0° and less than about 180°.

7. A method for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, the workpiece having a surface hardness, comprising increasing the surface hardness of the workpiece prior to forming or shaping the workpiece with the tool, or during forming or shaping of the workpiece with the tool, or both prior to and during forming or shaping of the workpiece with the tool.

8. A method as in claim 7, wherein the surface hardness of the workpiece is increased by at least one of a heat treatment, a chemical treatment, and a mechanical treatment.

9. A method for improving at least one of a surface finish and a surface integrity of a workpiece machined with a cutting tool, the workpiece having a surface hardness, comprising increasing the surface hardness of the workpiece during machining of the workpiece with the cutting tool, wherein the surface hardness of the workpiece is increased by cooling with a cryogenic fluid at least a portion of the cutting tool and at least a portion of the workpiece, and a jet of the cryogenic fluid impinges on a portion of the cutting tool at an impingement angle (α) greater than about 0° and less than about 90°, and the jet of the cryogenic fluid impinges on the surface of the workpiece at a spread angle (β) greater than about 0° and less than about 180°.

10. A method for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, comprising the steps of:

providing a supply of a cryogen;

providing a nozzle adjacent the workpiece, the nozzle having

at least one inlet adapted to receive a flow of the cryogen,

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet,

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion, and

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen;

delivering a portion of the cryogen to the at least one inlet of the nozzle, wherein the cryogen is at least partially separated within the downstream portion of the nozzle into a condensed phase portion and a vapor portion; and

jetting at least a portion of an expanding jet of the condensed phase portion and the vapor portion from the at least one outlet of the nozzle to the tool and a surface of the workpiece.

11. A method as in claim 10, wherein the downstream portion of the nozzle has at least one diverging wall and at least one converging wall adapted to converge on the expanding jet.

12. A method as in claim 11, wherein the at least one diverging wall has a diverging angle and the at least one converging wall has a converging angle less than the diverging angle.

13. A method as in claim 11, wherein the diverging wall is open to an ambient atmosphere.

14. A method for improving at least one of a surface finish and a surface integrity of a workpiece machined with a cutting tool, comprising the steps of:

providing a supply of a cryogen;

providing a nozzle adjacent the workpiece, the nozzle having

at least one inlet adapted to receive a flow of the cryogen,

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet,

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion, and

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen;

delivering a portion of the cryogen to the at least one inlet of the nozzle, wherein the cryogen is at least partially separated within the downstream portion of the nozzle into a condensed phase portion and a vapor portion; and

jetting at least a portion of an expanding jet of the condensed phase portion and the vapor portion from the at least one outlet of the nozzle to the cutting tool and a surface of the workpiece,

wherein the downstream portion of the nozzle has at least one diverging wall open to an ambient atmosphere and at least one converging

wall adapted to converge on the expanding jet, and wherein the at least one diverging wall has a diverging angle and the at least one converging wall has a converging angle less than the diverging angle.

15. A method for forming or shaping a workpiece having a surface hardness, comprising the steps of:

providing a tool adjacent the workpiece, the tool adapted to form or shape the workpiece;

forming or shaping the workpiece with the tool; and

increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool.

16. A workpiece formed or shaped by a method as in claim 15 and characterized by an improved surface finish, an improved surface integrity, or both an improved surface finish and an improved surface integrity.

17. A workpiece as in claim 16, said workpiece having a work surface roughness (Ra), wherein the work surface roughness (Ra) is equal to or less than a theoretical low roughness limit (Ra-t), calculated as $Ra\text{-}t=f^2 / (32\ r)$, where f is a cutting tool feedrate and r is a cutting tool nose radius.

18. A workpiece as in claim 16, wherein the workpiece has a formed or shaped work surface characterized by an improved residual stress, said improved residual stress being more compressive, deeper extending, or both more compressive and deeper extending than another residual stress that would be obtained by forming or shaping the

workpiece without increasing the surface hardness of the workpiece during forming or shaping of the workpiece.

19. A workpiece as in claim 16, wherein the workpiece contains at least one metallic alloy having at least one element selected from a group consisting of cobalt (Co), chromium (Cr), molybdenum (Mo), nickel (Ni), iron (Fe), tungsten (W), aluminum (Al), and titanium (Ti).

20. A workpiece as in claim 16, wherein at least a portion of the workpiece is in a form selected from a group consisting of a cast form, wrought form, powder metallurgy form, and composite form.

21. A workpiece as in claim 16, wherein the workpiece contains at least one polymer or at least one polymer-based composite.

22. A workpiece as in claim 16, wherein the workpiece has a formed or shaped work surface characterized by at least one of an improved fatigue strength, an improved fatigue life, an improved stress-cracking resistance, and an improved corrosion resistance.

23. A method for machining a workpiece having a surface hardness, comprising the steps of:

providing a cutting tool adjacent the workpiece, the cutting tool adapted to shape the workpiece;

shaping the workpiece with the cutting tool; and

increasing the surface hardness of the workpiece during shaping of the workpiece with the cutting tool, wherein the shaped workpiece is characterized by an improved surface finish having a work surface roughness (Ra) equal to or less than a theoretical low roughness limit (Ra-t), calculated as $Ra\text{-}t=f^2 / (32\ r)$, where f is a cutting tool feedrate and r is a cutting tool nose radius.

24. A method for manufacturing a finished part or a finished product from a workpiece having a surface hardness, comprising the steps of:

providing a tool adjacent the workpiece, the tool adapted to form or shape the workpiece;

forming or shaping the workpiece with the tool;

increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool; and

manufacturing the finished part or the finished product from the workpiece shaped or formed with the tool.

25. A method as in claim 24, wherein the finished part or the finished product is manufactured from the workpiece without using at least one additional operation needed by at least one other method for manufacturing a comparable finished part or a comparable finished product which the other method forms or shapes from a comparable workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during forming or shaping of the comparable workpiece, said at least one additional operation being selected from a group consisting of grinding, polishing, honing, deburring, peening, tumbling, burnishing, deep rolling, soft annealing, soft machining, soft shaping, soft forming, and work part cleaning.

26. A finished part or a finished product manufactured by a method as in claim 24 and characterized by a reduced manufacturing cost, said reduced manufacturing cost being less than a higher manufacturing cost for a comparable finished part or a comparable finished product manufactured by at least one other method which forms or shapes a comparable workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during forming or shaping of the comparable workpiece.

27. A method for manufacturing a finished part from a workpiece having a surface hardness, comprising the steps of:

providing a cutting tool adjacent the workpiece, the cutting tool adapted to shape the workpiece;

shaping the workpiece with the cutting tool;

increasing the surface hardness of the workpiece during shaping of the workpiece with the cutting tool; and

manufacturing the finished part from the workpiece shaped with the cutting tool,

wherein the finished part is manufactured from the workpiece without using at least one additional operation needed by at least one other method for manufacturing a comparable finished part which the other method shapes from a comparable workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during shaping of the comparable workpiece, said at least one additional operation being selected from a group consisting of grinding, polishing, honing,

deburring, peening, tumbling, burnishing, deep rolling, soft annealing, soft machining, soft shaping, soft forming, and work part cleaning.

28. An apparatus for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, the workpiece having a surface hardness, comprising means for increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool.

29. An apparatus as in claim 28, wherein the surface hardness of the workpiece is increased by cooling with a cryogenic fluid at least a portion of the tool, or at least a portion of the workpiece, or at least a portion of the tool and at least a portion of the workpiece.

30. An apparatus as in claim 29, wherein a jet of the cryogenic fluid impinges on a portion of the tool and a portion of a surface of the workpiece.

31. An apparatus as in claim 30, wherein the jet of the cryogenic fluid impinges on the portion of the tool at an impingement angle (α) greater than about 0° and less than about 90°.

32. An apparatus as in claim 30, wherein the jet of the cryogenic fluid impinges on the portion of the tool at an impingement angle (α) greater than about 30° and less than about 90°.

33. An apparatus as in claim 30, wherein the jet of the cryogenic fluid impinges on the surface of the workpiece at a spread angle (β) greater than about 0° and less than about 180°.

34. An apparatus for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, the workpiece having a surface hardness, comprising means for increasing the surface hardness of the workpiece prior to forming or shaping the workpiece with the tool, or during forming or shaping of the workpiece with the tool, or both prior to and during forming or shaping of the workpiece with the tool.

35. An apparatus as in claim 34, wherein the surface hardness of the workpiece is increased by at least one of a heat treatment, a chemical treatment, and a mechanical treatment.

36. A apparatus for improving at least one of a surface finish and a surface integrity of a workpiece machined with a cutting tool, the workpiece having a surface hardness, comprising means for increasing the surface hardness of the workpiece during machining of the workpiece with the cutting tool, wherein the surface hardness of the workpiece is increased by cooling with a cryogenic fluid at least a portion of the cutting tool and at least a portion of the workpiece, and a jet of the cryogenic fluid impinges on a portion of the cutting tool at an impingement angle (α) greater than about 0° and less than about 90°, and the jet of the cryogenic fluid impinges on the surface of the workpiece at a spread angle (β) greater than about 0° and less than about 180°.

37. An apparatus for improving at least one of a surface finish and a surface integrity of a workpiece formed or shaped with a tool, comprising:

a supply of a cryogen;

a nozzle adjacent the workpiece, the nozzle having

at least one inlet adapted to receive a flow of the cryogen,

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet,

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion, and

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen;

means for delivering a portion of the cryogen to the at least one inlet of the nozzle, wherein the cryogen is at least partially separated within the downstream portion of the nozzle into a condensed phase portion and a vapor portion; and

means for jetting at least a portion of an expanding jet of the condensed phase portion and the vapor portion from the at least one outlet of the nozzle to the tool and a surface of the workpiece.

38. An apparatus as in claim 37, wherein the downstream portion of the nozzle has at least one diverging wall and at least one converging wall adapted to converge on the expanding jet.

39. An apparatus as in claim 38, wherein the at least one diverging wall has a diverging angle and the at least one converging wall has a converging angle less than the diverging angle.

40. An apparatus as in claim 38, wherein the diverging wall is open to an ambient atmosphere.

41. An apparatus for improving at least one of a surface finish and a surface integrity of a workpiece machined with a cutting tool, comprising:

a supply of a cryogen;

a nozzle adjacent the workpiece, the nozzle having

at least one inlet adapted to receive a flow of the cryogen,

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet,

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion, and

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen;

means for delivering a portion of the cryogen to the at least one inlet of the nozzle, wherein the cryogen is at least partially separated within the downstream portion of the nozzle into a condensed phase portion and a vapor portion; and

means for jetting at least a portion of an expanding jet of the condensed phase portion and the vapor portion from the at least one outlet of the nozzle to the cutting tool and a surface of the workpiece,

wherein the downstream portion of the nozzle has at least one diverging wall open to an ambient atmosphere and at least one converging wall adapted to converge on the expanding jet, and wherein the at least one diverging wall has a diverging angle and the at least one converging wall has a converging angle less than the diverging angle.

42. An apparatus for forming or shaping a workpiece having a surface hardness, comprising:

a tool adjacent the workpiece, the tool adapted to form or shape the workpiece;

means for forming or shaping the workpiece with the tool; and

means for increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool.

43. A workpiece formed or shaped by an apparatus as in claim 42 and characterized by an improved surface finish, an improved surface integrity, or both an improved surface finish and an improved surface integrity.

44. A workpiece as in claim 43, said workpiece having a work surface roughness (Ra), wherein the work surface roughness (Ra) is equal to or less than a theoretical low roughness limit (Ra-t), calculated as $Ra\text{-}t=f^2 / (32\ r)$, where f is a cutting tool feedrate and r is a cutting tool nose radius.

45. A workpiece as in claim 43, wherein the workpiece has a formed or shaped work surface characterized by an improved residual stress, said improved residual stress being more compressive, deeper extending, or both more compressive and deeper extending than another residual stress that would be obtained by forming or shaping the workpiece without using a means for increasing the surface hardness of the workpiece during forming or shaping of the workpiece.

46. A workpiece as in claim 43, wherein the workpiece contains at least one metallic alloy having at least one element selected from a group consisting of cobalt (Co), chromium (Cr), molybdenum (Mo), nickel (Ni), iron (Fe), tungsten (W), aluminum (Al), and titanium (Ti).

47. A workpiece as in claim 43, wherein at least a portion of the workpiece is in a form selected from a group consisting of a cast form, wrought form, powder metallurgy form, and composite form.

48. A workpiece as in claim 43, wherein the workpiece contains at least one polymer or at least one polymer-based composite.

49. A workpiece as in claim 43, wherein the workpiece has a formed or shaped work surface characterized by at least one of an improved fatigue strength, an improved fatigue life, an improved stress-cracking resistance, and an improved corrosion resistance.

50. An apparatus for machining a workpiece having a surface hardness, comprising:

a cutting tool adjacent the workpiece, the cutting tool adapted to shape the workpiece;

means for shaping the workpiece with the cutting tool; and

means for increasing the surface hardness of the workpiece during shaping of the workpiece with the cutting tool, wherein the shaped workpiece is characterized by an improved surface finish having a work surface roughness (Ra) equal to or less than a theoretical low roughness limit (Ra-t), calculated as $Ra\text{-}t = f^2 / (32\ r)$, where f is a cutting tool feedrate and r is a cutting tool nose radius.

51. An apparatus for manufacturing a finished part or a finished product from a workpiece having a surface hardness, comprising:

a tool adjacent the workpiece, the tool adapted to form or shape the workpiece;

means for forming or shaping the workpiece with the tool;

means for increasing the surface hardness of the workpiece during forming or shaping of the workpiece with the tool; and

means for manufacturing the finished part or the finished product from the workpiece shaped or formed with the tool.

52. An apparatus as in claim 51, wherein the finished part or the finished product is manufactured from the workpiece without using at least one additional operation needed by at least one other apparatus for manufacturing a comparable finished part or a comparable finished product which the other apparatus forms or shapes from a comparable

workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during forming or shaping of the comparable workpiece, said at least one additional operation being selected from a group consisting of grinding, polishing, honing, deburring, peening, tumbling, burnishing, deep rolling, soft annealing, soft machining, soft shaping, soft forming, and work part cleaning.

53. A finished part or a finished product manufactured by an apparatus as in claim 51 and characterized by a reduced manufacturing cost, said reduced manufacturing cost being less than a higher manufacturing cost for a comparable finished part or a comparable finished product manufactured by at least one other apparatus which forms or shapes a comparable workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during forming or shaping of the comparable workpiece.

54. An apparatus for manufacturing a finished part from a workpiece having a surface hardness, comprising:

a cutting tool adjacent the workpiece, the cutting tool adapted to shape the workpiece;

means for shaping the workpiece with the cutting tool;

means for increasing the surface hardness of the workpiece during shaping of the workpiece with the cutting tool; and

means for manufacturing the finished part from the workpiece shaped with the cutting tool,

wherein the finished part is manufactured from the workpiece without using at least one additional operation needed by at least one other apparatus for manufacturing a comparable finished part which

the other apparatus shapes from a comparable workpiece having a comparable surface hardness without increasing the comparable surface hardness of the comparable workpiece during shaping of the comparable workpiece, said at least one additional operation being selected from a group consisting of grinding, polishing, honing, deburring, peening, tumbling, burnishing, deep rolling, soft annealing, soft machining, soft shaping, soft forming, and work part cleaning.

55. A nozzle for jetting an expanding jet of a cryogen to a surface of a workpiece, comprising:

at least one inlet adapted to receive a flow of the cryogen;

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet;

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion;

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen; and

means for separating the cryogen at least partially into a condensed phase portion and a vapor portion within the downstream portion of the nozzle.

56. A nozzle as in claim 55, further comprising an internal expansion chamber adapted to confine the expanding jet of the cryogen, wherein the nozzle is adapted to clamp a cutting tool having a tool rake surface.

57. A nozzle as in claim 55, wherein the downstream portion of the nozzle has at least one diverging wall and at least one converging wall adapted to converge on the expanding jet of the cryogen.

58. A nozzle as in claim 57, wherein the diverging wall has a diverging angle and the converging wall has a converging angle less than the diverging angle.

59. A nozzle as in claim 57, wherein the diverging wall is open to an ambient atmosphere.

60. A nozzle for jetting an expanding jet of a cryogen to a surface of a workpiece, comprising:

at least one inlet adapted to receive a flow of the cryogen;

an upstream portion in fluid communication with the at least one inlet, the upstream portion adapted to receive at least a portion of the flow of the cryogen from the at least one inlet;

a downstream portion in fluid communication with the upstream portion and adapted to receive at least a portion of the flow of the cryogen from the upstream portion;

at least one outlet in fluid communication with the downstream portion and adapted to receive and transmit from the downstream portion at least a portion of the flow of the cryogen;

means for separating the cryogen at least partially into a condensed phase portion and a vapor portion within the downstream portion of the nozzle; and

an internal expansion chamber adapted to confine the expanding jet of the cryogen,

wherein the downstream portion of the nozzle has at least one diverging wall open to an ambient atmosphere and at least one converging wall adapted to converge on the expanding jet of the cryogen, and

wherein the diverging wall has a diverging angle and the converging wall has a converging angle less than the diverging angle, and

wherein the nozzle is adapted to clamp a cutting tool having a tool rake surface.